Lattice rotation during severe local shear in a fully hardened Al-4%Cu-0.1%Fe single crystal alloy

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Abstract

EBSD revealed that the shear bands developed in fully hardened Al-4%Cu-0.1%Fe single crystals is formed by dense arrays of low angle boundaries (<3°), parallel to the band, originated by local lattice rotations due to slip on the conjugate system. When traversing the band, the TA swings repeatedly at discrete steps.

Keywords: Al-Cu, single crystals, EBSD, shear bands.

1. Introduction

It is well known that, when FCC single crystal metals, such as aluminum and aluminum alloys, are pulled in tension, a rotation of the tensile axis (TA) with respect the crystal axes occurs [1]. Such rotation, depicted in the stereographic triangle of Figure 1, is due to crystallographic slip on the (111) plane along the $[\bar{1}01]$ direction (so called the primary slip system, $(111)[\bar{1}01]$). This rotation progresses until the symmetry boundary of the stereographic triangle, $[001]-[\bar{1}11]$, is reached. At this point, two slip systems, the primary, $(111)[\bar{1}01]$, and the conjugate, $(\bar{1}\bar{1}1)[011]$, are equally oriented for slip and become activated. Thus, according to geometrical considerations, rotation of the TA should continue along the symmetry boundary, towards the $[\bar{1}12]$ crystal direction (Figure 1). This prediction, initially proposed by Taylor back in 1938 [2], was put forward for pure metals and alloys assuming homogeneous deformation. Extensive experimental work has been carried out in pure metals such as copper [3,4], aluminum [4] and solid solution alloys, such as Al-Cu alloys in the as-quenched condition [5-9], with the aim of verifying the fulfillment of Taylor´s prediction.

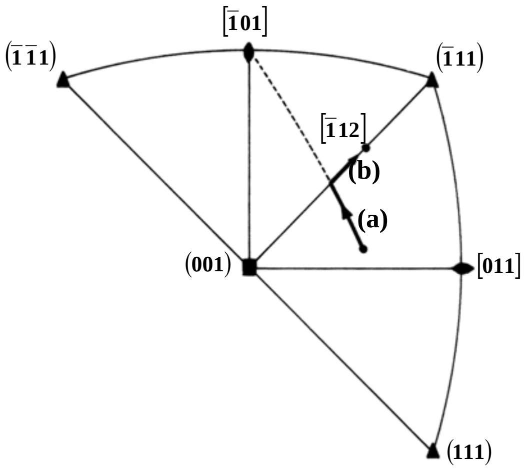

Figure 1. Theoretical rotation of the TA in an fcc single crystal as a consequence of the activation of (a) the primary slip system and, (b) of the primary and conjugate slip systems, simultaneously.

It is worth pointing out the dramatically different mode of fracture observed when Al-Cu single crystal alloys are tested after appropriate treatment for a fully hardened, T6, condition [8]. At the onset of plastic deformation these alloys start deforming by slip on the primary slip system. Failure of the crystals occurs in the absence of necking, sometimes after some overshooting (about 3° [9]) of the TA over the $[001]-[\bar{1}11]$ symmetry boundary, and as a consequence of a severe local shear, due to the sudden local activation of slip on the conjugate $(\bar{1}\,\bar{1}\,1)[011]$ slip system. In order to elucidate the specific mechanisms accounting for this mode of failure, it would be desirable to know the local lattice rotations occurring within the shear bands developed.

Previous studies [9-12], conducted by means of conventional X-ray diffraction techniques such as the Laue [10-12], the rotating crystal, or the diffractometer methods [9], have proved to be appropriate for the determination of the crystal rotation during deformation at a "macroscopic" scale. These procedures are, however, not suitable for the investigation of lattice rotations at the microscopic level. Recent advances in microstructural characterization techniques allow measuring lattice orientations in submicrometer areas [13-17]. Electron backscatter diffraction (EBSD), in particular, has proved to be an essential tool for the investigation of local orientations and grain boundary distributions in a wide range of fine grained materials [13]. A number of recent studies have investigated the lattice rotation during plastic deformation of single crystals using EBSD [14-16]. All of them point toward the fact that Taylor´s predictions are not fulfilled at a local level, i.e., when a sufficiently small domain is analyzed. For example, Wert et al. [14,15] studied the microstructure developed during tensile extension, up to 30%, of an Al [110] single crystal oriented for multiple slip in 4 equally stressed systems. They observed that, among all of them, only two slip systems become activated, the primary at the onset of plastic deformation and the conjugate after an elongation of 10%. Simultaneously, they observe the subdivision of the microstructure into two kind of bands, ones in which only slip on the primary system takes place, and others in which both slip of the primary and conjugate slip systems is observed. The latter are, respectively, subdivided into smaller domains in which either the primary or the conjugate slip system operate. Thus, these studies suggest the discretization of macroscopic deformation into local domains where single slip is active. Han et al. [16] give a similar perspective of local deformation. They also observed the subdivision of the microstructure into two sets of intermingled small units. In the first group, the TA moves from its initial orientation in the non deformed Al toward the $[001]-[\bar{1}11]$ symmetry boundary. In the second group the TA moves, also from its initial orientation, *parallel to* the symmetry boundary.

The purpose of the present study is, therefore, to investigate further the specific lattice rotations that occur in the local shear bands formed in Al-4%Cu-0.1%Fe single crystals heat treated to a fully hardened condition (T6 treatment). To achieve this goal, local orientations within and in the vicinity of the shear bands of three crystals with different initial orientations were determined using the EBSD technique.

2. Experimental procedure

The composition and the initial microstructure of the Al-4%Cu-0.1%Fe alloy is described elsewhere [8]. The alloy was supplied in the form of 7 mm diameter rods (extruded and drawn) from which single crystals were grown by a strain-anneal method. This method consists on imposing a critical tensile strain, optimal for maximum grain growth after recrystallization at 540ºC, and then submerging the rods in a salt bath at this temperature. The critical tensile strain imposed was 1.7% and the rate at which the rods were submerged was 8.2 mm/h. Single crystals up to 300 mm in length were obtained. The orientation of each single crystal rod axis was obtained by the Laue diffraction method.

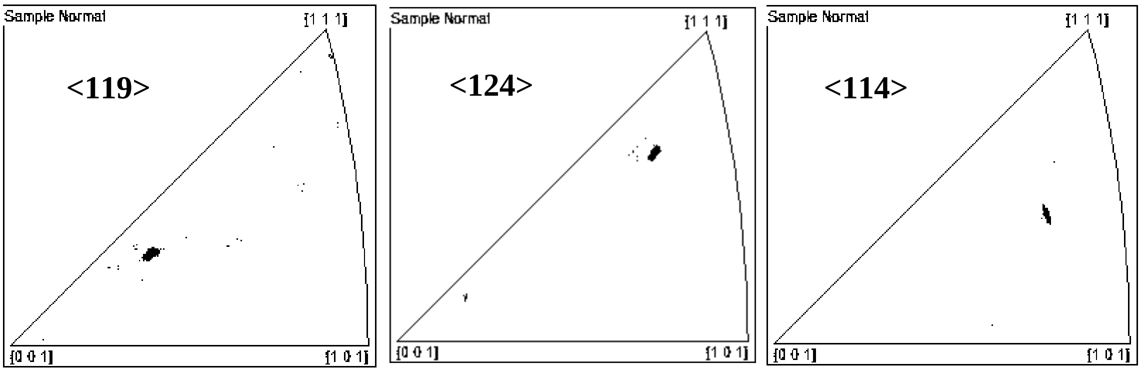

Figure 2.- Standard stereographic triangles showing the initial orientation of the rod axes (TA) of the Al-4%Cu-0.1%Fe single crystals examined as obtained by EBSD.

Three single crystals were selected, whose rod axes are positioned in the standard stereographic triangle as depicted in Figure 2. From each crystal, two tensile specimens, with a 30 mm gage length and a 5.5 mm diameter, were machined. Before the tests, the samples were electropolished in order to facilitate the macroscopic observation of the slip lines that developed during testing. The electro-polishing solution consisted in 400 ml of methanol, 200 ml of nitric acid and 25 ml of butyl-glycol. The samples were tested in the T6 condition [8]. Tensile tests were conducted at a initial strain rate of $10^{-5}s^{-1}$. The tests were interrupted at the point where a localized shear bands appeared, usually triggered by the activation of the conjugate slip system. The onset of the severe local shear could be observed by careful examination of the sample gage length during testing, allowing interruption of the test before failure could occur. The strains at which the shear bands appeared in the three single crystals studied were, respectively, 18.2% <119>, 18.5% <124>, and 34.1% <114>.

Macroscopic examination of the slip lines within and in the vicinity of the shear bands was carried out by sectioning the gage length along a longitudinal plane. The local orientations, both within the shear bands and in the nearby regions, were analyzed by EBSD in a JEOL SEM operated at 20 kV using the Oxford Instruments' INCA (Crystal) software located at the Universidad Politécnica de Valencia, Spain. Careful sample preparation for EBSD examination included the same electropolishing procedure used for the observation of the slip lines and localized shear bands formation during testing. Due to the high surface reactivity of the Al-Cu-Fe alloy studied, microtexture examination was carried out immediately after electropolishing.

3. Results and discussion

In the following, the microtexture data corresponding to regions within the shear bands and outside the band will be shown. Figure 3 summarizes the micro and mesotexture developed within the shear bands of the three crystals. As it becomes apparent from the observation of the inverse pole figures, the TA within the band is spread along an "orientation path" starting in the $[001]-[\bar{1}11]$ symmetry boundary toward the [011] corner of the stereographic triangle. Since EBSD allows to determine isolated orientations, without any correlation with the undeformed condition, it is not possible to establish whether overshooting has occurred or not. Overall, rotation angles as high as 12° have been measured. This observation, which is particularly clear for the <124> and <114> crystals (Figs. 3b and 3c), is consistent with the activation of single slip on the conjugate system. Additionally, the spread in orientations indicates that lattice rotation and deformation by shear on this system are not homogeneous throughout the band thickness. The scattering of individual orientations is wider in the <119> single crystal that in the other two. This is explained by the fact, whereas in the <124> and <114> crystals the "orientation paths” resulting from the primary and conjugate slip systems overlap significantly (although the rotation caused by each slip system takes place in opposite senses), in the case of the <119> crystal this overlap is minimal.

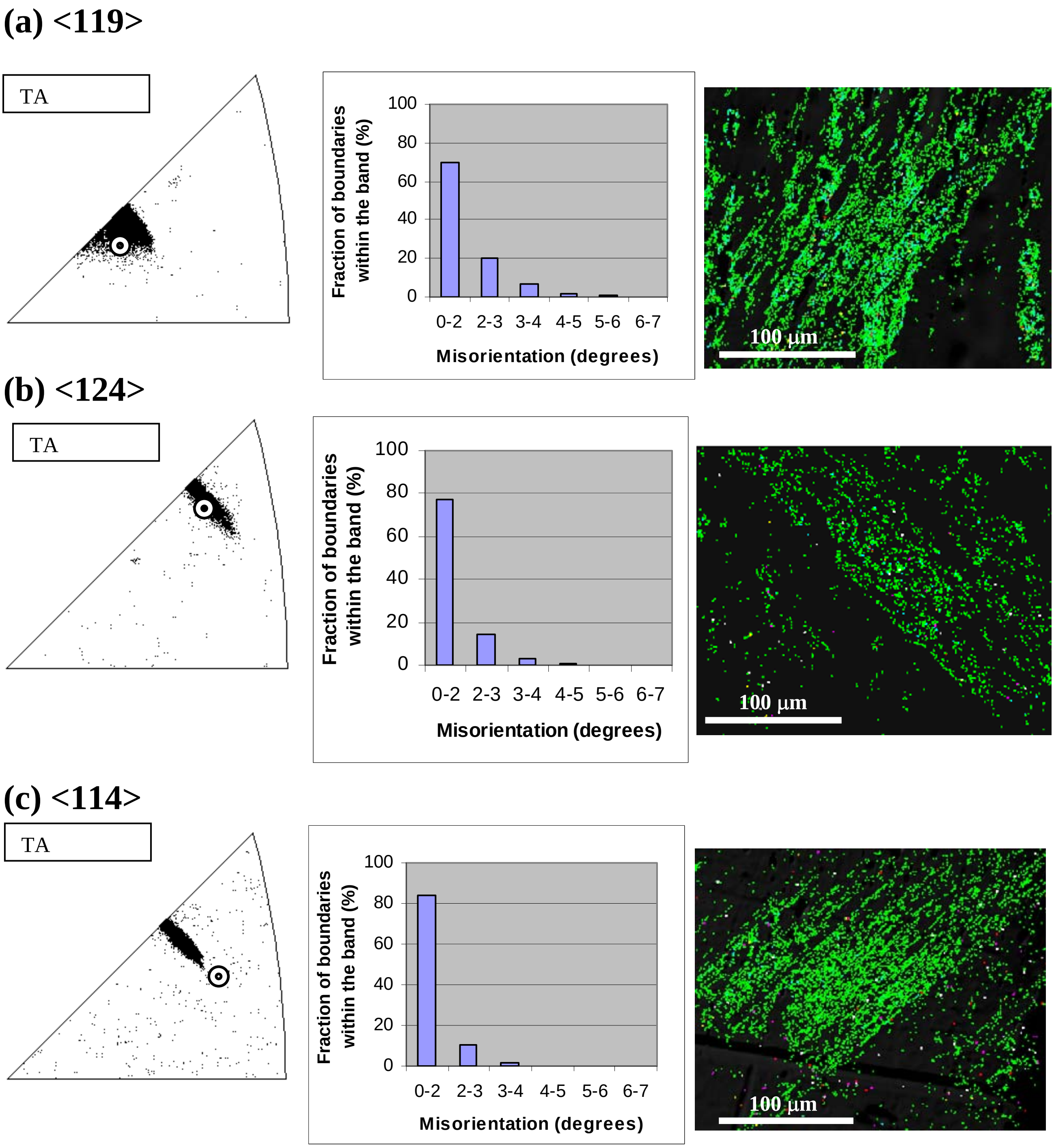

Figure 3. Microtexture within the band of the three Al-4%Cu-0.1%Fe single-crystals investigated: Inverse pole figures showing the orientation path followed by the TA within the band, misorientation distribution histogram illustrating the presence of subboundaries within the band, and boundary map showing the array of subboundaries lying parallel to the band edges. The starting orientation of the TA is illustrated.

Figure 3 also illustrates the nature of the boundaries developed within the band by means of misorientation distribution histograms. It can be clearly seen that subboundaries, with misorientations smaller than 4°, develop as a consequence of the interaction between dislocations sliding in the conjugate slip system and those already present due to previous slip on the primary system. As can be observed in the adjacent boundary maps, these subgrain boundaries lie parallel and define the shear band. Thus, lattice rotations within the band take place at discrete steps, always smaller than 4°. When traversing the sheared area, the TA swings back and forth along the “orientation path” illustrated in the inverse pole figures of Fig. 3, as a consequence of the development of the observed substructure, as drawn schematically in Figure 4. The orientation of the TA in zones away from the sheared area, where only single slip on the primary system occurs, is illustrated in Figure 5 by means of inverse pole figures for the <119> (Fig. 5a) and <124> (Fig. 5b) crystals. It can be seen that, in all cases, the TAs tend to group close to the symmetry boundary in the stereographic triangle. This is consistent with Taylor´s prediction of the lattice rotation taking place as a consequence of the activation of the primary slip system.

In accordance with recent investigations on the local microstructure development in single crystals under tension [14-17], the data presented in this paper show that deformation within the shear bands developed in Al-Cu single crystals treated in the T6 condition is highly heterogeneous. The presence of a large density of subboundaries within the shear bands indicates that deformation on a local scale takes place at discrete steps.

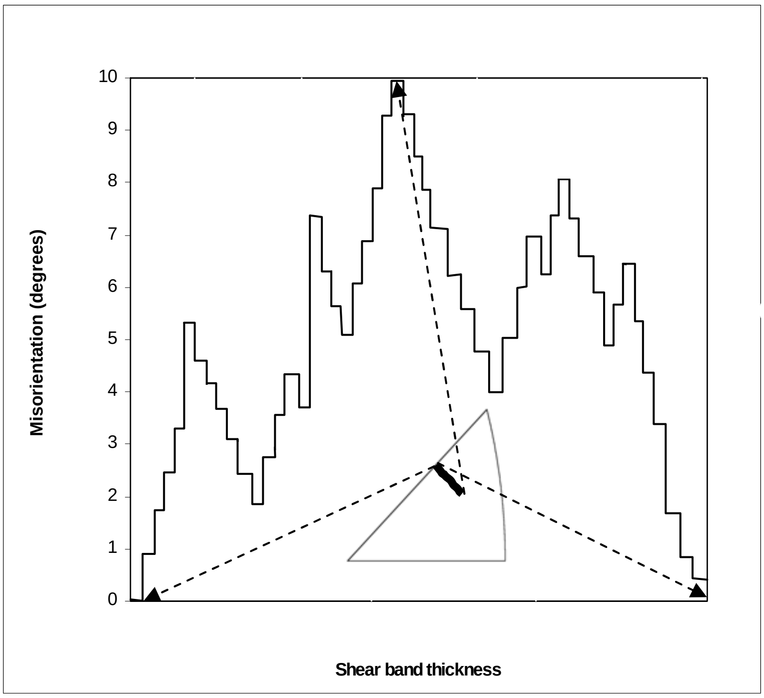

Figure 4. Illustration of the orientation shifts taking place within an idealized shear bands in which the TA has rotated up to about 10º from the $[001]-[\bar{1}11]$ symmetry boundary. The inverse pole figure points out the hypothetic orientation path of the TA in which the start and end orientations correspond to specific regions in the shear bands thickness, as indicated by the arrows.

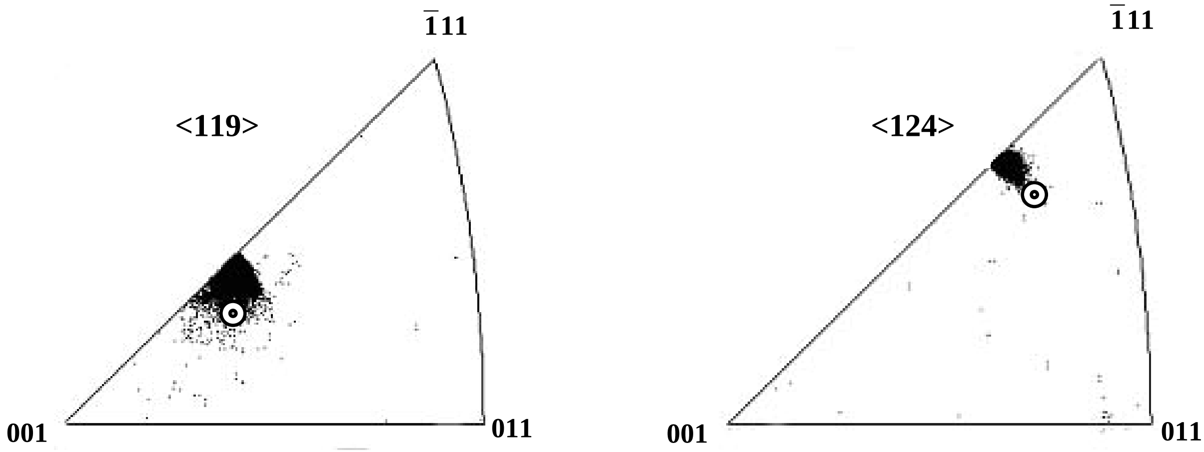

Figure 5. Inverse pole figures showing the orientation of the TA within the gage length in areas away from the shear bands in two of the deformed single crystals investigated. The starting orientation of the TA is illustrated.

4. Summary

The lattice rotation taking place within the shear bands developed upon the activation of the conjugate slip system in three fully hardened Al-4%Cu-0.1%Fe single crystals has been investigated by means of EBSD. Deformation within the band is highly heterogeneous. Subboundaries, parallel to the band edges, develop as a consequence of the interaction between dislocations sliding in the conjugate slip system and those already present due to previous slip on the primary system. Thus, lattice rotations take place at discrete steps, always smaller than 4°. The TA within the band swings back and forth defining an orientation path, starting at the $[001]-[\bar{1}11]$ symmetry boundary, towards the [011] corner of the stereographic triangle.

Acknowledgements

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